

Experimental and theoretical evaluations of electron temperature in continuous electron beam generated plasmas

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Abstract

In this paper an experimental and theoretical evaluation of electron temperature in continuous, electron beam generated plasmas is presented. Spatial distributions of electron temperature and plasma density in pure and diluted argon were measured. The dependence of the electron temperature and plasma density on pressure, gas composition, hollow cathode voltage and magnetic field was investigated as well. It was observed that the electron temperature in argon was less than 1 eV and that a small addition of nitrogen reduced the electron temperature even more. The magnetic field, pressure and beam current did not strongly affect the electron temperature but greatly influenced the plasma density. The experimental findings are supported by analytical estimations of electron temperature in both noble and molecular gases.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

Electron beams have been employed successfully for a variety of applications including gas lasers [1] surface treatments [2], decontamination of high-volume exhaust streams [3], negative ion extraction [4,5] and the enhancement of plasma properties (where the beam is injected into existing plasma) [6]. The electron beams that are of interest in this study are formed by extraction from a plasma. The source plasma can be produced using a magnetron [7], arc [7], glow [8] or hollow cathode [9] discharges. The latter type is often referred to in the literature as ‘plasma cathode electron guns’, and the electron beam source used in this study belongs to this category. The development of plasma cathode electron guns dates back to at least the 1970s for welding applications [9, 10]. Since then many such sources have been developed, working in a large range of currents (0.7–600 A), voltages (1–200 kV), pressures (10^{-4} – 10^{-1} Torr) and for use in a wide range of applications. The continuous electron beam source developed at NRL has electron beam currents and voltages up to 0.1 A and 2 kV, respectively and operates over a pressure range from 5×10^{-3} to 5×10^{-2} Torr.

In discharges an external electric field is applied to heat the plasma electrons in order to ionize, dissociate and excite the background gas. In this case, the fundamental

plasma characteristics, e.g. electron temperature and plasma density, are controlled by the source type and operating conditions. Discharges used for material processing typically have densities of 10^9 – 10^{12} cm⁻³ and electron temperatures (T_e) in the range 1–10 eV [11]. The electron temperature determines the plasma potential and thus determines the minimum ion energy at surfaces located adjacent to the plasma. The incident ion energy strongly influences the particular material processing application, which can range from sputtering to crosslinking. However, for treatment of sensitive materials like polymers the incident ion energy must be low [12] to avoid damaging the surface.

Electron beam-produced plasmas have an intrinsically lower electron temperature, and this affects materials processing in several ways. First, in the absence of any external bias, the ion energy incident on a material is much lower (<5 eV) compared with discharges, and therefore surface roughening or other damage to sensitive materials is reduced. And second, when a bias is applied to raise the ion energy, the spread in energy is less, and consequently better regulated. Fernsler [13] first predicted that the electron temperature of molecular gases in beam generated plasmas should be less than 1 eV. Later, Langmuir probe measurements in a pulsed electron beam plasma source confirmed these estimates [14, 15].

The purpose of this paper is to show and explain why the electron temperature in electron beam generated plasmas is

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considerably lower than in discharges. The electron energy distribution, which determines the plasma-driven chemistry and collision rates, is Maxwellian-like in discharges, and therefore the ionization rate varies roughly as $\exp(-W_i/T_e)$, where W_i is the ionization energy of the gas molecules. The ionization rate is thus appreciable only if T_e is not too small. Moreover, for a Maxwellian-like distribution, far more energy is deposited into the excited states, which lie below W_i . In electron beam-produced plasma there are two classes of electrons: the high-energy electrons responsible for gas ionization; and the low-energy secondary electrons, which are typically born hot (in contrast to discharges) but quickly cool in the absence of external electric fields. The energy distribution is again Maxwellian-like at low energy but not at high energy. Inelastic collisions with gas molecules cause the high-energy electrons to lose energy such that the population of low-energy electrons grows and becomes large. The low-energy electrons are eventually destroyed by processes like recombination and diffusion. Because the low-energy electrons are far more numerous, they control the key plasma properties, and they are cooled electrostatically as well as collisionally. As a result the electron temperature is *lower* than in discharges, and therefore the plasma potential and ion energy are also small. Thus, these sources can provide large fluxes of low-energy ions to surfaces [14].

The use of high-energy beams has other benefits as well. Because the ionization cross sections are similar for all gases at high electron energy (e.g. $8 \times 10^{-17} \text{ cm}^2$ for Ar^+ [16], $7 \times 10^{-17} \text{ cm}^2$ for N_2^+ [17], $6 \times 10^{-17} \text{ cm}^2$ for O_2^+ [17] at 1000 eV), the types of ions produced by beams can be easily controlled by adjusting the gas composition. The ionization cross sections are larger than the cross sections for excitation for multi-kilovolt electrons, and nearly half of the energy deposited by a beam goes into ionization. In argon for example, the cross sections at 1000 eV are approximately $2 \times 10^{-17} \text{ cm}^2$ for excited Ar^* [18, 19] and $4 \times 10^{-19} \text{ cm}^2$ for the metastable Ar^{*m} [19, 20]. Therefore, fewer excited molecules (especially metastables) are produced and the gas is less perturbed. Indeed, the ionization efficiency can reach 30% or more in all gases [6].

This paper is organized as follows: first, probe diagnostics are presented. This includes measurements of the electron temperature and plasma density and their spatial profile in argon, the effects of gas pressure and magnetic field on the electron temperature and plasma density on-axis, the influence of gas composition by introducing nitrogen and the effect of hollow cathode voltage variation. Second, the electron temperature is estimated analytically and then compared with the probe results. The estimates in both noble and molecular gases agree well with the experimental results, thus confirming that the electron temperature in electron beam plasmas is less than 1 eV for noble gases like argon and even lower for molecular gases.

2. Experimental apparatus

2.1. Chamber design

The experimental apparatus is shown in figure 1. The chamber consists of a stainless steel cross (50 cm from flange to flange)

mounted on a large cylindrical base. The system vacuum was maintained by a 100 L s^{-1} diffusion pump that provides base pressures in the 5×10^{-6} range. Mass flow controllers were used to supply gas to the chamber. The purity of gases used in these experiments was 99.999% for argon and >99.8% for nitrogen. A Convectron[®] vacuum gauge was used to determine operating pressures, and the reported readings were corrected for the gas used. The electron beam was extracted from a hollow cathode positioned on top of the chamber and was accelerated through a slotted anode at ground potential. The beam is terminated by a final ground anode located approximately 50 cm away at the bottom of the chamber. The magnetic field directed along the electron beam axis was generated with a pair of Helmholtz coils. The magnetic field strength in all the experiments (except when stated otherwise) was 100 G.

2.2. Hollow cathode design

The dc discharge in the hollow cathode produces electrons that are extracted through a wire-grid anode and then accelerated to produce an energetic electron beam. The discharge thus determines the beam current, while the accelerating voltage determines the beam energy. The hollow cathode operates at a few hundred volts with respect to a wire-grid anode, which is held at a large negative voltage (up to -5 kV) with respect to a grounded plate containing a rectangular slot. The hollow cathode has a rectangular cross section with 6.5 cm width, 18.5 cm length and 7 cm depth with a rectangular opening (2 cm wide and 14 cm long) located at the end adjacent to the wire-grid anode. Electrons produced in the hollow cathode pass through the grid (1 cm wide and 10 cm long) and then through a slot in a planar anode. This slotted anode is positioned approximately 1 cm from the grid and has an opening 2 cm wide and 14 cm long. The grid consisted of a stainless steel mesh with 36% transmission and openings of $60 \times 60 \mu\text{m}^2$. A justification for choosing this grid is provided below. The hollow cathode, the grid and the slotted anodes were made from stainless steel. Between them, ceramic and Teflon insulators were used. The hollow cathode was cooled by water. Two dc power supplies (-500 V , 10 A and -5 kV , 1 A) were used for the hollow cathode discharge and beam acceleration, respectively. Connections of the electrical outputs of the power supplies to the electrodes are shown in figure 1.

The openings in the stainless steel mesh were chosen to optimize beam extraction and prohibit plasma leakage. Sheaths form on both sides of the grid because of the plasma surrounding it, and if the holes in the grid are too large, plasma from either side can penetrate the grid. Hence, the grid should be as fine as possible, durable and have a high transmission. The holes should be smaller than the sheath which is several Debye lengths thick. The Debye length λ_D is determined by the electron temperature and the electron density n_s at the sheath edge. In particular, if $T_e \approx 2 \text{ eV}$ and $n_s \approx 10^{10} \text{ cm}^{-3}$ inside the hollow cathode plasma [21], $\lambda_D \approx 74 \mu\text{m}$. In this case, a grid with openings of $60 \times 60 \mu\text{m}^2$ should work well.

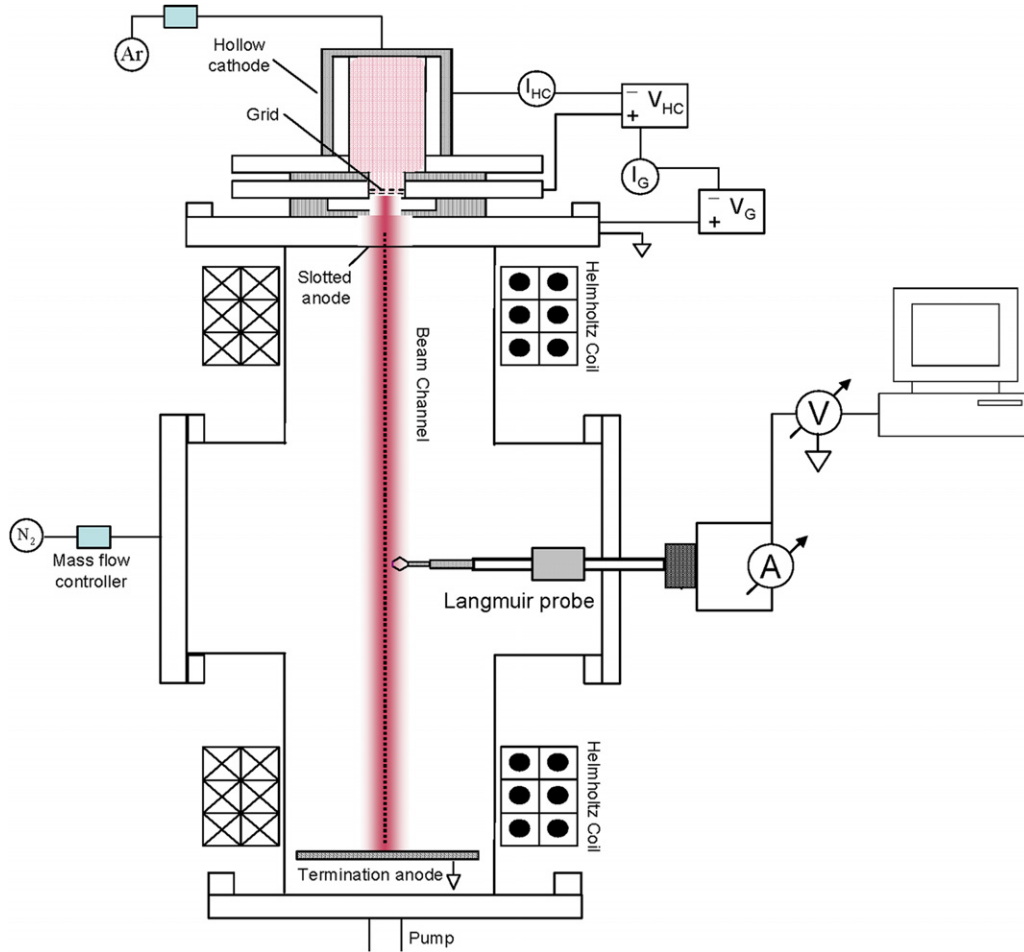


Figure 1. Schematics of the experimental chamber and incorporated Langmuir probe diagnostics. V_{HC} and V_g denote hollow cathode and grid voltage, respectively. I_{HC} and I_g signify hollow cathode and grid currents.

2.3. Langmuir probe construction, data collection and analysis

The Langmuir probe was constructed from ceramic and stainless steel tubes. The tip was a loop of tungsten wire with an exposed area of $2.5 \times 10^{-3} \text{ cm}^2$. Langmuir probe I – V characteristics were created by plotting the measured current versus the applied bias voltage. The probe was heated at a constant current of 2.5 A to prevent oxidation and contamination of the tungsten. The Langmuir probe was operated in an emissive mode to determine the plasma potential. A LabVIEW™ program [22] was used to control the bias source (Stanford Research SR245, Keithley 2400) and to perform the data analysis. The probe voltage was increased from -15 to 15 V in 0.02 V steps, and the voltage and current at each step were collected and stored in a master ASCII data file. A data analysis routine was used to determine the plasma electron temperature (T_e), the plasma potential (V_p), the floating potential (V_f) and the electron density (n_e). The plasma potential was determined first from the maximum of the derivative of the I – V characteristic. The probe current data was then fitted using a function of the form $I(V) = a + b(-\varphi)^\gamma + c[\exp(\varphi/T_e)]$, where $\varphi = V - V_p$. The first two terms represent the ion portion of the trace while the third term models the electron current. The exponent γ depends on

the effective geometry of the probe (0.5 for a cylinder and 1 for a sphere), and the constants a , b and c are all parameters used to fit the data. The prefactor c is the electron saturation current, given by $c = en_e A (kT_e / 2\pi m_e)^{1/2}$, where e is the electron charge, A is the probe area, k is Boltzmann's constant and m_e is the electron mass. Values of a , b and c are found for a series of T_e values, with the best combination of values being the set that minimizes the error between the data and the fit. With the best c and T_e values, the electron density is finally calculated from the expression given above for c . No allowance was made for the beam current because the beam density was much smaller than the plasma density in all experiments.

Beam–plasma instabilities are an obvious concern in this device and were addressed in [13]. In that work, collisions and a large spread in axial beam velocity were shown to suppress the instabilities, and indeed Langmuir probes and most other diagnostics have shown no evidence of oscillations. Microwave emission was, however, detected at the plasma frequency and harmonics of the electron cyclotron frequency [23]. While the emission exceeded background, it was nevertheless weak and appeared at frequencies too high (above 1 GHz) to be detected by a Langmuir probe. There is thus no need to filter out these low-level, microwave fluctuations.

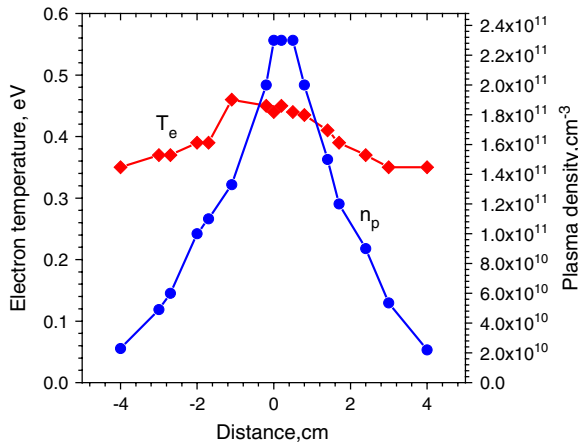


Figure 2. Spatial plasma density and electron temperature profiles in argon. Experimental conditions: pressure 20 mTorr, grid voltage 1.3 kV, grid current 19 mA, hollow cathode voltage 360 V, hollow cathode current 35 mA, magnetic field strength 100 G.

3. Experimental results

Spatial distributions of the electron temperature and plasma density in a plasma produced in pure argon are shown in figure 2. The pressure in the chamber was 20 mTorr. The grid voltage and current were 1.3 kV and 19 mA, respectively. The hollow cathode voltage and current were 360 V and 35 mA. The magnetic field strength was 100 G. The estimated plasma potential for argon was 2.6 V. The electron temperature was 0.45 eV and was approximately constant inside the beam (the variation was less than 10%). Then it fell to 0.35 eV outside the beam, which is consistent with the absence of a significant potential drop within the ionization region. Note that the plasma density across the width of the beam was approximately constant as well. However, a voltage drop is expected outside the beam and there the electron temperature fell. The plasma density fell rapidly outside the beam (from $2.3 \times 10^{11} \text{ cm}^{-3}$ in the middle of the beam to $2.2 \times 10^{10} \text{ cm}^{-3}$ outside the beam).

The effect of pressure on the electron temperature and plasma density at the beam axis is presented in figure 3. The grid and the hollow cathode voltages were 1.3 kV and 320 V, respectively. The hollow cathode and grid currents increased with pressure. The on-axis electron temperature was 0.6 eV from 30 to 50 mTorr and then fell to 0.4 eV at 20 mTorr. The difference in T_e (from 0.45 to 0.4 eV) in figures 2 and 3 at 20 mTorr was caused by operating the hollow cathode at a lower voltage (from 360 to 320 V) and the hollow cathode current difference was 13 mA. The plasma density increased by almost an order of magnitude from 10^{11} cm^{-3} at 20 mTorr to $8 \times 10^{11} \text{ cm}^{-3}$ at 50 mTorr. This is because the hollow cathode plasma density and thus beam current increase with pressure. Similar behavior was observed when the hollow cathode voltage was increased as shown in figure 5.

The magnetic field influence on electron temperature and plasma density is presented in figure 4. The pressure was held constant at 50 mTorr. The grid and the hollow cathode voltages were 1.3 kV and 360 V, respectively. The hollow cathode and grid currents increased with magnetic field strength but the electron temperature was nearly constant, $T_e \approx 0.6 \text{ eV}$. The

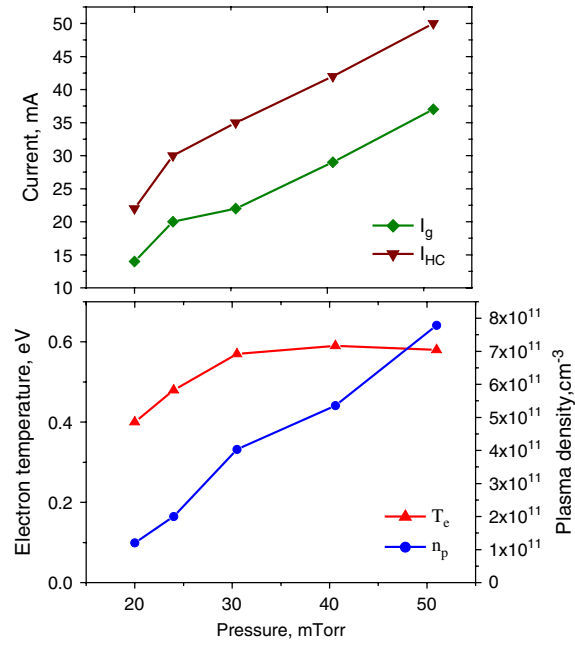


Figure 3. Effect of pressure on electron temperature and plasma density in argon plasma. The measurements were performed in the middle of the electron beam. Experimental conditions: grid voltage 1.3 kV, hollow cathode voltage 320 V, magnetic field strength 100 G.

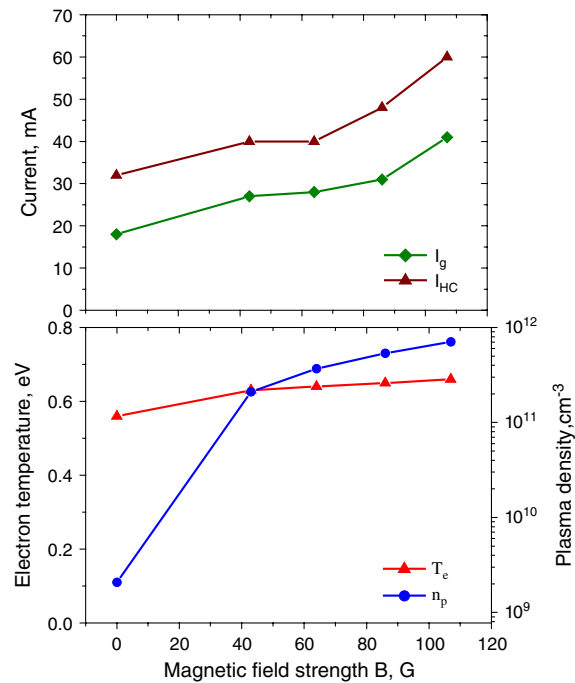


Figure 4. Effect of magnetic field on electron temperature and plasma density in argon plasma. The measurements were performed in the middle of the electron beam. Experimental conditions: pressure 50 mTorr, grid voltage 1.3 kV, hollow cathode voltage 360 V.

large increase in plasma density from $2 \times 10^9 \text{ cm}^{-3}$ with no magnetic field to $7 \times 10^{11} \text{ cm}^{-3}$ for a magnetic field of 110 G is due to the fact that the magnetic field retards diffusion, which is the main electron loss mechanism. Furthermore, the magnetic field serves to collimate the electron beam and thus to increase the plasma density on axis.

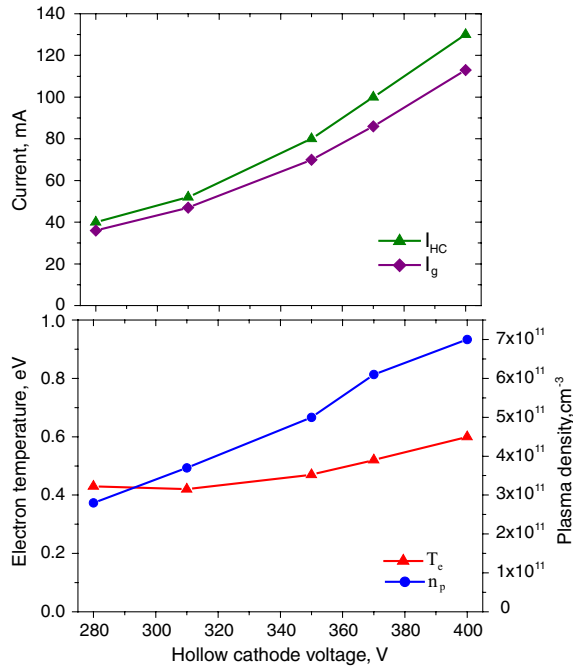


Figure 5. Effect of hollow cathode voltage on electron temperature and plasma density in an argon–nitrogen mixture (93/7 vol%). The measurements were performed in the middle of the electron beam. Experimental conditions: pressure 50 mTorr, grid voltage 0.8 kV, hollow cathode voltage 280 V, magnetic field strength 128 G.

The effect of the hollow cathode voltage on the electron temperature and plasma density is presented in figure 5. The measurements were performed in an argon–nitrogen mixture (93% Ar, 7% N_2). In this experiment the pressure was 50 mTorr, the grid and hollow cathode voltages were 0.8 kV and 280 V, respectively. The magnetic field strength was 130 G. As the hollow cathode current increased from 40 to 120 mA, the plasma density increased from 3×10^{11} to $7 \times 10^{11} \text{ cm}^{-3}$. The electron temperature also changed slightly, from 0.4 to 0.5 eV.

The effect of gas composition on the electron temperature and plasma density is shown in figure 6. The pressure was again 50 mTorr. The grid and hollow cathode voltages were 1.3 kV and 350 V, respectively. The hollow cathode and grid currents changed from $I_{HC} = 55 \text{ mA}$ and $I_g = 44 \text{ mA}$ in pure argon to $I_{HC} = 80 \text{ mA}$ and $I_g = 60 \text{ mA}$ in 50% Ar and 50% N_2 mixture and remained at those levels even in pure nitrogen. The plasma potential in pure nitrogen was 2 V. The highest electron temperature, 0.7 eV, was measured in pure argon. The difference between this value and the T_e of 0.6 eV, obtained in figures 3 and 4, might be due to the higher beam current ($\approx 10 \text{ mA}$). Only 10% N_2 addition was sufficient to reduce the electron temperature to 0.45 eV, and T_e remained at 0.45 eV even in pure nitrogen. This is because nitrogen, unlike argon, has many excited states (especially vibrational) at energies below 10 eV. Thus, even small concentrations of nitrogen greatly increase the energy-loss rate at low energy. In addition, charge exchange converts many of the atomic argon ions into molecular nitrogen ions, which then recombine with the plasma electrons. As a result, the plasma density fell as well, from $8 \times 10^{11} \text{ cm}^{-3}$ in pure argon to 10^{11} cm^{-3} in pure

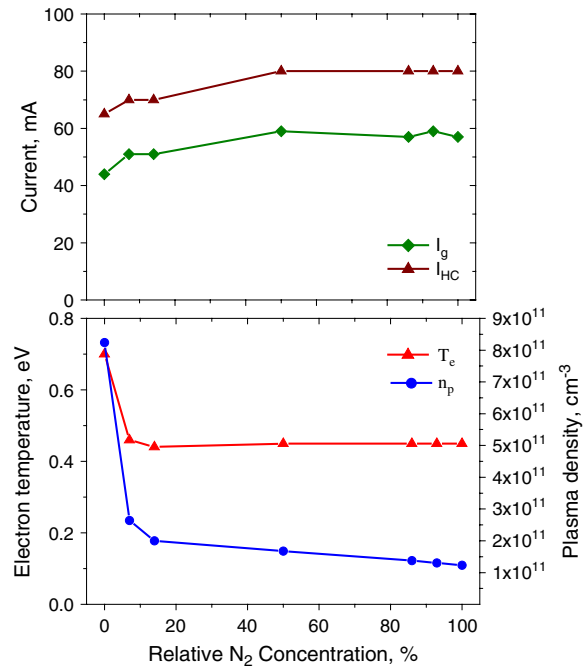


Figure 6. Effect of gas composition on electron temperature and plasma density. The measurements were performed in the middle of the electron beam. Experimental conditions: pressure 50 mTorr, grid voltage 1.3 kV, hollow cathode voltage 350 V, magnetic field strength 100 G.

nitrogen. Note that attachment plays no role in nitrogen or argon and that cluster ions like N_4^+ do not have time to form at low pressure.

4. Discussion

The gas pressure, the hollow cathode voltage and the magnetic field strongly influenced the plasma density but affected the electron temperature only weakly. The magnetic field was applied along the beam direction (z -axis) to confine the beam to a thin sheet. But the magnetic field retards the outward flow of plasma electrons even more, especially in argon, which has a strong Ramsauer minimum [15]. In this case, electron pressure must overcome the magnetic force as well as ion drag, and therefore the electron temperature increased slightly when the magnetic field was introduced. The only parameter that strongly influenced the electron temperature was the gas composition, and even a slight addition of molecular gas (N_2) was sufficient to reduce the electron temperature significantly.

To understand why the electron temperature is low ($< 1 \text{ eV}$) in electron beam generated plasmas, recall that as beam electrons pass through a gas, they produce secondary electrons with energies ranging from zero up to half the beam energy minus the ionization energy W_i of the gas molecules. The secondaries produce additional ionization, and both they and the primaries lose energy to other types of collisions as well. Most of the beam electrons pass through the gas, whereas most secondaries remain trapped by collisions and the magnetic field. The high-energy tail of the electron energy distribution therefore soon equilibrates [24,25], but the number of low-energy electrons grows until the electrons are physically

destroyed. The mean electron energy therefore becomes small in beam-produced plasmas, despite the presence of an extended high-energy tail [26, 27].

Electron–electron collisions drive the energy distribution towards a Maxwellian at low energy but are inconsequential at high energy. The high-energy tail is therefore strongly non-Maxwellian, but its population is too small to have much direct effect on the mean energy or the temperature T_e as measured by a Langmuir probe. Nevertheless the energetic electrons do affect T_e . To show this, divide the electrons into two groups: those with energies above W_i and those with energies below W_i . Only electrons in the first group can ionize, and therefore these electrons determine the total volumetric gas ionization rate S_b . But once the energy of an electron falls below W_i , it becomes a member of the second group. Electrons in the second group are far more numerous and are termed ‘plasma electrons’ because they control the bulk plasma properties. We will consider this population further.

The beam and its progeny generate daughter electrons with a probability varying roughly as $(\varepsilon_s^2 + \varepsilon_o^2)^{-1}$, where ε_s is the initial energy of a daughter electron and the constant ε_o is a fraction of the ionization energy W_i of the gas molecules [28]. For example, ε_o/W_i equals 0.73 in nitrogen and 0.55 in argon. Given this probability function, the average energy of electrons born with energies between zero and W_i satisfies

$$\frac{3T_o}{2} \approx \left(\frac{\varepsilon_o}{2}\right) \frac{\ln[1 + (W_i/\varepsilon_o)^2]}{\tan^{-1}(W_i/\varepsilon_o)}. \quad (1)$$

Particle simulations and Boltzmann calculations have confirmed this estimate [29, 30]. Since all plasma electrons have energies below W_i by definition, the mean energy of electrons just entering the plasma group equals $3T_o/2$. For example, in nitrogen $3T_o/2 \approx 6.4$ eV based on $W_i = 15.6$ eV. If all daughter electrons eventually become plasma electrons, the volumetric plasma creation rate equals S_b , and therefore the volumetric plasma electron heating rate equals $(3T_o/2)S_b$. However, this energy is quickly redistributed through collisions with the gas molecules and other electrons. As a result, T_e soon falls well below T_o , and the energy distribution becomes Maxwellian-like at low energy. Since the plasma electrons are not heated externally, T_e is lower than in discharges, even though electrons are born cold in discharges.

The plasma electrons are usually hotter and more mobile than the ions, and they therefore escape faster initially. As a result, the plasma charges positive, and this charge slows the outward flow of electrons but accelerates the outward flow of ions. Energy is thus transferred electrostatically from the plasma electrons to the ions, so T_e falls. To model electrostatic cooling in more detail, neglect collisional cooling and assume the flow velocity u_e of the plasma electrons is small compared with their thermal speed, $(T_e/m)^{1/2}$, where m is the electron mass. In steady state, the energy equation for the plasma electrons then reduces to

$$\nabla \cdot \left(n_e u_e \frac{5T_e}{2} + Q_e \right) = \left(\frac{3T_o}{2} \right) S_b + e n_e u_e \nabla \phi, \quad (2)$$

where Q_e is the plasma electron heat flux and ϕ is the electrostatic potential. The heat flux vanishes at the walls but can be large inside, in which case T_e is nearly uniform across the plasma. In the absence of sinks, the electron continuity equation is given by

$$\nabla \cdot (n_e u_e) = S_b. \quad (3)$$

Note that the magnetic field plays no direct role in either equation and that the electrostatic potential ϕ is the only possible energy sink in equation (2).

The potential ϕ is zero at the grounded walls encircling the plasma. Thus, if we integrate equation (2) by parts over the plasma volume, we obtain

$$\begin{aligned} \frac{5\bar{T}_e}{2} \dot{N}_e &= \frac{3T_o}{2} \dot{N}_e + \int d(\text{vol}) [\nabla \cdot (e n_e u_e \phi) - e \phi \nabla \cdot (n_e u_e)], \\ &= \frac{3T_o}{2} \dot{N}_e - e \bar{\phi} \dot{N}_e. \end{aligned} \quad (4)$$

Here the total plasma production rate is given by

$$\dot{N}_e = \int d(\text{vol}) S_b, \quad (5)$$

while the mean temperature and potential are defined as

$$\bar{T}_e = \frac{1}{\dot{N}_e} \int d(\text{vol}) S_b T_e \quad (6)$$

$$\bar{\phi} = \frac{1}{\dot{N}_e} \int d(\text{vol}) S_b \phi. \quad (7)$$

If ionization occurs mainly near the plasma center, $\bar{\phi}$ and $\bar{T}_e$ roughly equal the potential and temperature at the center. Taking T_e to be constant, equation (4) then reduces to

$$T_e \approx 0.6T_o - 0.4e\phi_o, \quad (8)$$

where ϕ_o is the potential in the plasma middle. Note that if ϕ_o were zero, T_e would be slightly less than T_o , because of the work done by electron pressure. However, in practice ϕ_o is positive, to balance the electron and ion currents leaving the plasma. The plasma potential ϕ_o consists of a voltage drop $\Delta\phi_s$ across the sheaths plus a voltage drop $\Delta\phi_b$ from the sheaths to the plasma center. If the voltage drop in both regions is mainly a function of T_e , equation (8) predicts that T_e will be nearly independent of the gas pressure, magnetic field and system geometry. The data plotted in figures 3 and 4 support this claim.

The plasma potential ϕ_o is difficult to compute in magnetized plasmas, because the plasma flow is in general non-ambipolar and differs along and across the field. However, if the sheaths are thinner than the electron gyroradius, electrons in the sheaths are effectively unmagnetized and consequently the voltage drop across the sheath satisfies

$$e\Delta\phi_s = T_e \ln \left(\frac{1}{g} \sqrt{\frac{M}{2\pi m}} \right). \quad (9)$$

Here M is the ion mass, and g is the ratio of the local ion flux to the local electron flux. Equation (9) is a generalization of the ambipolar result ($g = 1$) given in [31].

The total outflow of electrons and ions is equal in steady state, and therefore g equals unity when averaged over all the walls. Consequently, the mean sheath drop is close to the ambipolar value evaluated at $g = 1$, unless $g \geq 0.1(M/2\pi m)^{1/2}$ over a large fraction of the total wall area. The voltage drop $\Delta\phi_b$ from the sheaths to the plasma middle is no less than $0.5T_e$ based on the Bohm condition [32], and therefore the plasma potential in the middle satisfies

$$e\phi_o \geq 0.5T_e[1 + \ln(M/2\pi m)]. \quad (10)$$

Inserting this result into equation (8), we obtain

$$T_e \leq \frac{0.6T_o}{1 + 0.2 \ln(M/2\pi m)}. \quad (11)$$

Note that although the magnetic field strongly affects the electron diffusion tensor, it has only a weak effect on the electron temperature [15]. Equation (11) applies in pure noble gases only and was obtained by ignoring collisional cooling. Collisional cooling is unimportant only at energies below the lowest metastable energy W_m , and therefore the initial temperature T_o should be computed using W_m in place of W_i in equation (1). In argon $W_m = 11.55$ eV while $\varepsilon_o = 8.75$ eV, so $T_o \cong 3.2$ eV. Inserting this value into equation (11) leads to $T_e \leq 0.7$ eV, which agrees with the obtained experimental values. This result is only approximate, of course, and it makes no allowance for spatial variations in T_e . Nonetheless, the temperatures predicted by this model agree reasonably well with the values measured on-axis.

A somewhat better estimate for $\Delta\phi_b$ can be obtained by assuming no magnetic field and planar, ambipolar flow. (Recall that the magnetic field had little effect on T_e in figure 4.) Using the Bohm condition, flux conservation and the Boltzmann relationship, one can show that the voltage drop from the ionization region to the sheath edge then satisfies $e\Delta\phi_b \cong T_e \ln(1 + b\nu_+/c_s)$. Here b is the distance from the ionization region to the walls, $c_s = (T_e/M)^{1/2}$ is the ion sound speed, $\nu_+ \cong 5 \times 10^{-10}N$ is the ion-neutral collision frequency, and N is the gas density in cm^{-3} . The temperatures predicted by this model agree well (within 10%) with the values measured on-axis.

The preceding model applies only to noble gases at low pressure. At high pressure, three-body collisions with neutrals rapidly convert atomic ions into molecular ions, while binary collisions strongly retard the flow. As a result, dissociative recombination becomes more important than diffusion [26, 27]. In addition, elastic electron-neutral collisions occur so rapidly that they become the primary electron cooling mechanism. Consequently, at high pressure, noble gases behave much like molecular gases, except that T_e is higher because of the lack of low-lying excited states.

Let us now estimate the plasma electron temperature for dense plasmas formed by electron beams in non-attaching molecular gases like nitrogen. In these gases the plasma electrons lose energy mainly to inelastic collisions with the gas molecules, and most of the electrons eventually recombine with molecular ions via dissociative recombination: $e + AB^+ \rightarrow A + B$. In the plasma middle the molecular ion

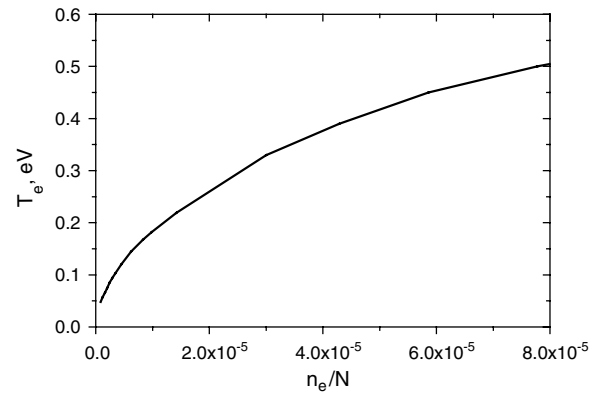


Figure 7. Electron temperature estimate based on swarm data [33] in nitrogen.

density is approximately equal to the electron density n_e , and therefore the recombination rate is approximately equal to the generation rate, $\beta n_e^2 \cong S_b$, based on particle balance. Here, the recombination coefficient β depends on T_e only. Similarly, the local volumetric cooling rate for the plasma electrons is approximately equal to $n_e s_c N$, where N is the gas density and s_c is the reduced, inelastic energy-loss rate for electrons with energies below W_i . Note that s_c depends only on T_e and the cutoff energy W_i . The heating and cooling rates balance in steady state:

$$\frac{3}{2} T_o S_b \approx n_e s_c(T_e) N, \quad (12)$$

and therefore S_b can be eliminated to produce a transcendental expression for T_e as a function of the degree of ionization:

$$\frac{s_c(T_e)}{\beta(T_e)} \approx \left(\frac{3T_o}{2} \right) \left(\frac{n_e}{N} \right). \quad (13)$$

Equation (13) is justified in molecular gases but not in noble gases for two reasons. First, β is effectively zero for atomic ions, and electrons thus diffuse to the walls well before they recombine. Second, in noble gases the lowest excited state lies at an energy W_m that is not much smaller than the ionization energy W_i . For example, $W_m = 11.55$ eV while $W_i = 15.8$ eV in argon. As a result, the collisional energy-loss rate is negligible in noble gases at energies below W_m .

Measurements of n_e can be used to estimate T_e in gases like nitrogen, given $s_c(T_e)$ and $\beta(T_e)$. The reduced collisional cooling rate $s_c(T_e)$ equals a sum of the various energy-loss rates integrated over the electron energy distribution. To avoid calculating $s_c(T_e)$ directly, swarm data is used instead. In a swarm discharge $s_c = w_d e E / N$, where the electron drift velocity w_d is a function of the reduced electric field E/N . The characteristic electron energy, $\varepsilon_k \cong T_e$, is also a function of E/N , and from that data $s_c(T_e)$ can be determined. Using data tabulated by Dutton [33] and setting $\beta(T_e) = 4 \times 10^{-8} T_e^{-0.37} \text{ cm}^6 \text{ s}^{-1}$ with T_e in eV [34], values of T_e as a function of n_e/N are plotted in figure 7 for pure nitrogen. According to the plot, $T_e \cong 0.47$ eV for $n_e = 10^{11} \text{ cm}^{-3}$ in 50 mTorr ($N \cong 1.65 \times 10^{15} \text{ cm}^{-3}$) of N_2 . This value agrees well with the experimentally measured value of 0.44 eV.

5. Conclusions

In this paper, the plasma electron temperature and plasma density were measured in plasmas generated by a continuous electron beam. The temperature in these plasmas was found to be lower than that in conventional (discharge) sources, especially in molecular gases. Spatial profiles of the plasma electron temperature and density were presented in pure argon and showed a peak in both the electron temperature and plasma density along the beam axis. In addition, the effects of gas pressure, magnetic field, hollow cathode voltage and gas composition on the plasma were investigated. Gas composition was the only parameter that greatly influenced the electron temperature, and the plasma density was lower in nitrogen due to recombination. Simple theoretical models were presented to explain the electron temperature in beam-produced plasmas, and the theoretical predictions agree well with the measurements in both noble and molecular gases. In short, the measurements confirm that electron beams can produce dense, low electron-temperature plasmas in any type of gas, a property that is important when processing sensitive materials or when producing dense ion-ion plasmas.

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